*Nuclear Heating, Radiation Damage, and Waste Management Options for the HYLIFE-II Final Focus Magnets**

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Abstract

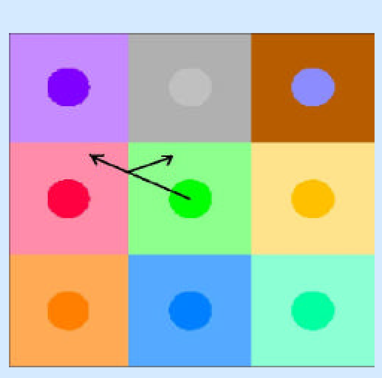
Heavy-ion fusion (HIF) designs for inertial fusion energy (IFE) power plants typically require final focusing magnets just outside the reaction chamber and blanket. Due to penetrations within the chamber and blanket, the magnets are exposed to a radiation environment. Although the magnet bores would be sized to avoid line-of-sight irradiation, the magnets still would be susceptible to nuclear heating and radiation damage from neutrons and gamma-rays. Additionally, the magnets must be included in waste management considerations due to substantial neutron activation. Modified versions of the HYLIFE-II IFE power plant featuring two-sided illumination by arrays of 32 and 96 beams from each side are presented. A simple, point-of-departure quadrupole magnet design with minimal shielding is assumed, and a three-dimensional neutronics model is created for the Flibe pocket, first wall, blanket, shield, and final two or three sets of focusing magnets. This work details state-of-the-art neutronics calculations and shows that the final focus system needs to be included in the economic and environmental considerations for the driver-chamber interface of any HIF IFE power plant design.

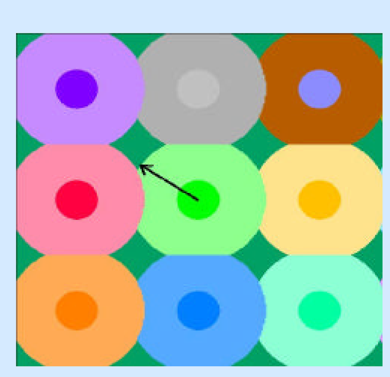
Introduction and Previous Work

- Despite shielding from line-of-sight radiation, magnets will still be exposed to significant quantities of radiation
- Shielding of magnets is important for several reasons; one seeks to:
  - Reduce nuclear heating to ensure that magnets do not quench
  - Reduce neutron and γ-ray radiation damage such that magnets have a reasonable lifetime
  - Reduce nuclear heating such that the recirculating power is not unreasonably high
  - Reduce neutron activation to allow recycling or disposal via shallow land burial
- Previous work has addressed some of these issues, but work may be incomplete or impractical given recent trends towards a greater number of beams:
  - Previous designs (HIBALL, HIBALL-II, Osiris) typically used 12-20 beams and allocated 30-40 cm of shielding on the inner bore of each magnet[1-3]
  - HYLIFE-II allowed only 3 cm of shielding, but detailed final focus neutronics calculations were not completed[4]
- Current work on final focus designs calls for more beams and less shielding for each magnet[5]:
  - More beams allows less current per beam, and thus, smaller magnets
  - To best enable thick-liquid protection schemes, arrays with small half-angle are desirable
  - Smaller size per beam is required
  - Forces designs with less shielding
- Due to symmetry of most designs and complexity of magnet shielding calculations of this type, previous work has often resorted to modeling only a portion of the reactor geometry (e.g., one-half of one beam line in a system that has 20 beams = 1/40 model)[1-2]:
  - A portion of the geometry can be modeled correctly using planes
  - One cannot use conical reflectors as these artificially bias the results in an unpredictable manner

Why Conical Reflectors Don't Work[6]

- Basic problem related to fact that one cannot fill all space with cones without overlap or gaps between the cells
- As a result, the results can be biased in an unpredictable manner:
  - This effect has been verified using TART, MCNP, and COG (this is **not** a code error)
  - All three codes give you the same *wrong* answer
- A 2-D example is used to demonstrate the error introduced when a cylindrical reflector is used:



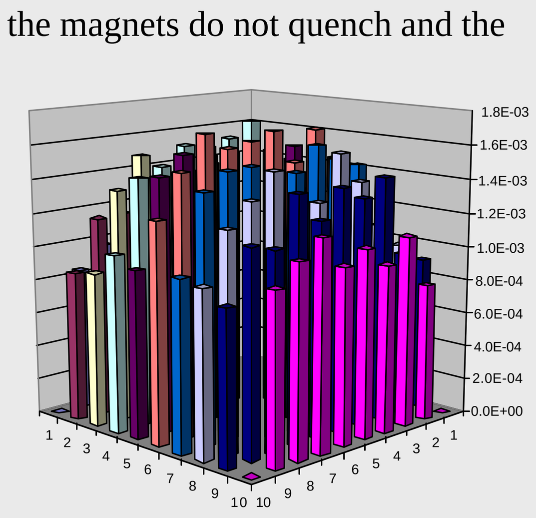


On left is a square repeating lattice. On the right is a cylindrical approximation, where the radii are defined such that the volumes are conserved. Assume that in each case we replace the repeating lattice by a single cell and reflecting surfaces. On the left, only the center square is used, surrounded by four reflecting planes. On the right, only the center cylinder is used, where the cylinder itself is a reflecting surface.

Now consider a neutron emitted at the center of each cell travelling outward toward the reflecting boundary. On the left we can see that if the neutron reflects off of the bounding plane it ends up moving in the same relative direction as if it had been allowed to pass through the plane, i.e., in this case the trajectory is not biased. In contrast, on the right we can see that ALL neutrons emitted at the center are traveling in a direction orthogonal to the surface of the reflecting cylinder. Therefore, when these neutrons reflect off of the bounding cylinder they are reflected back along their path, directly toward the origin, i.e., in this case the trajectory of the particles is biased toward the center of the cylinder.

Nuclear Heating and Cooling Power

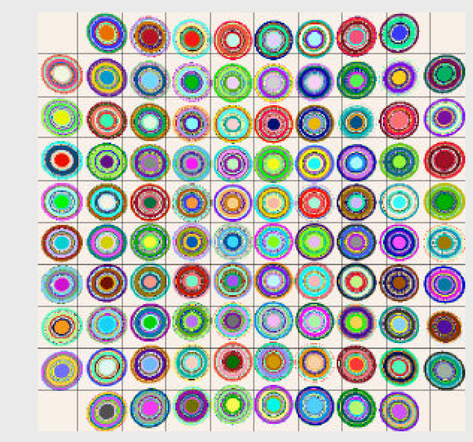
- Nuclear heating of the magnets must be limited to ensure that the magnets do not quench and the cooling power is not excessive:
  - For pool boiling, limit for Nb-Ti is ~ 100 mJ/cc[7]
  - With forced-flow cooling, one can allow more heating
- Nuclear heating results:
  - 64-beam cases: 1.6 - 2.6 × 10^{-4} J/cc in coil regions
  - 192-beam cases: 1.0 - 3.4 × 10^{-3} J/cc in coil regions
- Cooling power results:
  - 64-beam cases: 12.4 - 18.0 MW for cooling of all magnets
  - 192-beam cases: 8.3 - 21.1 MW for cooling of all magnets (shielding blocks in front/between magnets requires additional 58 MW if heat removed at LHe temperature)
- Afterheat removal not included:
  - Afterheat of NbTi + Cu regions add steady-state power of 5.2 × 10^{-4} W/cc in 192-beam case



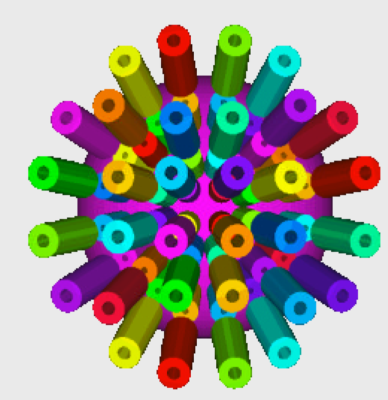
Magnets at the interior of the array are subject to greater nuclear heating than those on the outside.

Neutronics Models

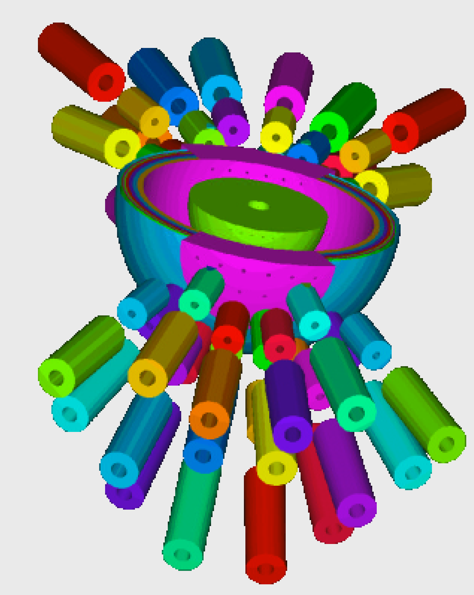
- HYLIFE-II uses thick-liquid jets of Flibe to provide line-of-sight shielding for the first wall[4]
- HYLIFE-II used single-sided illumination/12 beams; two modified versions are modeled here:
  - 32 beams per side in 6 × 6 array with corners removed
  - 96 beams per side in 10 × 10 array with corners removed
- In 64-beam case, final two quadrupole magnets modeled:
  - Last set of quadrupoles are staggered to obtain a more compact final focus system
  - Only one magnet modeled with detailed radial build
- In 192-beam case, last three quadrupole magnets modeled:
  - No staggering of magnets; radial build for all
  - More aggressive (compact) magnet design
  - Difficulties in obtaining sharp edge to Flibe jets addressed with in-chamber Flibe vortices



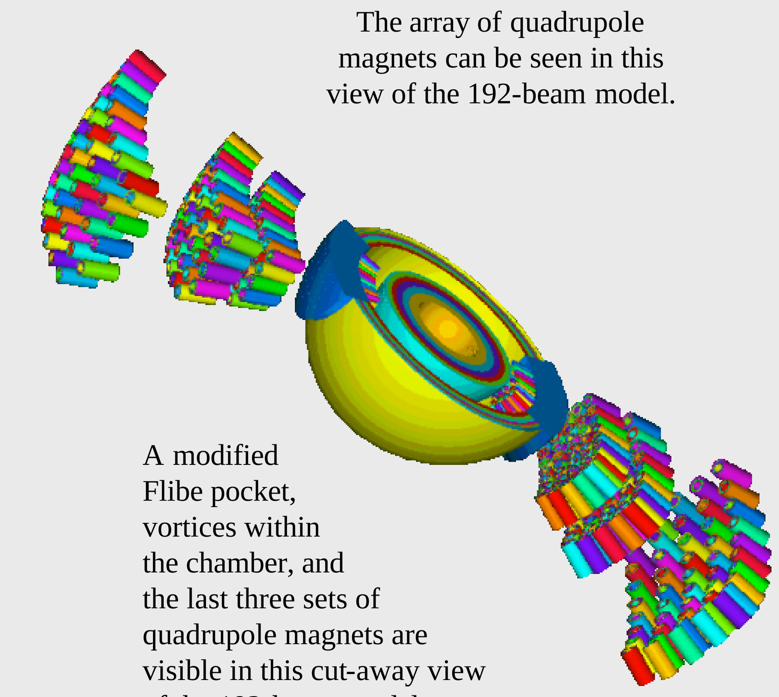
The array of quadrupole magnets can be seen in this view of the 192-beam model.



View that the target might have as it approaches the target chamber in the 64-beam model.



32 beams (and 64 magnets) are visible in this cut-away view. The Flibe pocket appears in green.



A modified Flibe pocket, vortices within the chamber, and the last three sets of quadrupole magnets are visible in this cut-away view of the 192-beam model.

- Detailed radial build of each magnet is important for several reasons:
  - Needed to obtain radiation damage and nuclear heating in insulators, superconductors, and stabilizers
  - Power needed to remove 1 watt depends upon temperature of the region; we assume efficiencies:
    - 2:1 for water cooled regions
    - 20:1 for liquid nitrogen (LN_2) cooled regions
    - 200:1 for liquid helium (LHe) cooled regions
- Radial build of the 192-beam magnet design given at right (a similar radial build was used in the 64-beam mode)

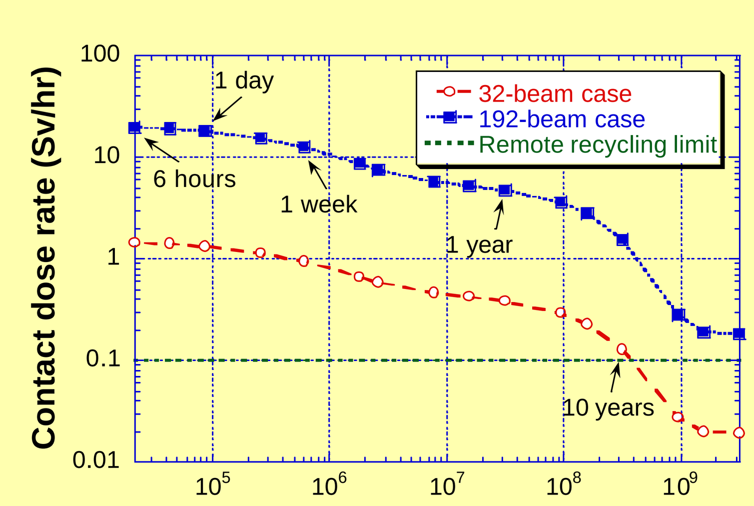
Component	Inner radius	Component	Inner radius
Inner bore[a]	0-8.70	Insulation	11.19
SS316	8.70	W shielding	12.19
He gas	9.02	LN_2	15.31
SS316	9.34	SS316	15.91
Insulation	9.50	Insulation	16.07
W shielding	10.50	SS316	17.07
He gas	10.75	NbTi+Cu+LHe[b]	17.32
W shielding	11.06	SS316	19.32/0.36

[a] Inner bore is tapered down to 5.9 cm radius at front of magnets; space is filled with tungsten shielding.
[b] Note: lack of exterior insulation and coil clamp would necessitate use of cooled structure for support

Radiation Damage and Neutron Activation Results

- Radiation doses to the conductors have been calculated in Gy/year of operation; previous work[1] reported a dose limit of ~ 5 × 10^7 Gy to epoxy electrical insulators
- Other work[7] reported a 2.5% increase in resistivity of Cu at fluences of only ~ 2 × 10^{17} n/cm²
- Hahn et al.[8] report a 2× reduction in the critical current density and a 3 K drop in the critical temperature for Nb_3Sn irradiated to 2 × 10^{18} n/cm²

Index	64-beam cases	192-beam cases
Annual fluence (n/cm²) to conductor, stabilizer, and insulators	1.9-2.7 × 10^{18} n/cm²	1.7-3.4 × 10^{19} n/cm²
Annual dose (Gy) to conductor, stabilizer, and insulators	4.2-6.9 × 10^6 Gy/y	3.0-9.9 × 10^7 Gy/y
Displacements per atom to conductor and stabilizer	1.4-2.3 × 10^{-3} dpa/y	Not calculated



Contact dose rates from the NbTi+Cu coils following 30 years of irradiation.

- Contact dose rates are dominated by different elements and isotopes at various times:
  - ^{46}Sc, ^{48}Sc, ^{60}Co, ^{64}Cu, and ^{92}Nb from NbTi superconductor and Cu stabilizer at early times (out until days)
  - ^{60}Co from Cu stabilizer at intermediate times (days to years)
  - ^{94}Nb from NbTi superconductor at long decay times (> 10 years)
- A dose rate of < 100 mSv/hr may allow remote maintenance on activated components (typically, 25 μSv/hr is required for hands-on maintenance):
  - Activation ~ 10× lower in 64-beam cases than in 192-beam cases
  - Even in 64-beam cases, remote recycling difficult before ~ 10 yr cooling
  - If magnets experience only 3 yr irradiation, then recycling contact dose rate achieved after 2.5 yr of decay
- Due to high contact dose rates, it appears difficult to recycle the windings from superconducting magnets:
  - Waste disposal rating (WDR) < 1 indicates that disposal via shallow land burial may be possible
  - For 64-beam cases, 35 ≤ WDR ≤ 52
  - For 192-beam cases, 380 ≤ WDR ≤ 570
- Nb_3Sn will not have a more favorable result due to Nb
- Waste volumes are also important:
  - If magnets are lifetime components, waste volumes for the superconductors and stabilizers are 85 m³ in the 64-beam cases and 5 m³ in the 192-beam cases
  - Doses in 192-beam cases are ~ 10-20× higher, and thus, waste volume is probably ~ 50-100 m³

Conclusions and Recommendations

- Detailed magnet shielding calculations are needed and are now possible with advanced neutronics modeling
- Nuclear heating appears to be acceptable in all cases, even once radioactive afterheat is included; improvement is desirable to reduce cooling power:
  - Reduction may be possible by switching to aluminum stabilizers and titanium alloys for structural materials[9]
- Radiation doses and fluences to conductors, stabilizers, and insulators have been calculated:
  - Data is extremely sparse; more is needed
  - Limited data suggests that significant radiation-induced effects (e.g., decreased critical field, increased resistivity, etc.) will occur after only 0.5-3 years of operation
- Significant neutron activation makes recycling and shallow land burial of magnets appear difficult; resulting waste volumes rival those from first wall/blanket
- Additional work is needed to increase shielding effectiveness of current designs and consider alternates (normal conductors?) in an attempt to achieve an overall balance between performance, economics, and safety and environmental considerations

References and Acknowledgments

[1] M. E. Sawan, W. F. Vogelsang, and D. K. Sze, Radiation shielding of heavy ion beam focusing magnets in HIBALL, University of Wisconsin, Fusion Engineering Program, UWFDM-438 (Aug. 1981).
[2] HIBALL-II: An improved conceptual heavy ion beam driven fusion reactor study, Kernforschungszentrum Karlsruhe, KfK 3840 (Jul. 1985).
[3] R. F. Bourque, W. R. Meier, and M. J. Monsler, Overview of the Osiris IFE reactor conceptual design, Fusion Technol. 21 (1992) 1465-1469.
[4] R. W. Moir, Improvements to the HYLIFE-II inertial fusion power plant design, Fusion Technol. 26 (1994) 1169-1177.
[5] E. P. Lee, Lawrence Berkeley National Laboratory, personal communication (Aug. 1999).
[6] D. E. Cullen, see online reflection tutorial at: http://reddog1.llnl.gov
[7] Y. Iwasa, Case studies in superconducting magnets, Plenum Press, New York (1994).
[7] R. A. van Konynenburg, M. W. Guinan, and J. H. Kinney, Fusion neutron damage in superconductors and magnet stabilizers, Second topical meeting on fusion reactor materials (1981).
[8] P. A. Hahn, M. W. Guinan, L. T. Summers, T. Okada, and D. B. Smathers, Fusion neutron irradiation effects in commercial Nb_3Sn superconductors, J. Nucl. Matl. 179-181 (1991) 1127-1130.
[9] M. Zucchetti, E. Medda, and G. Miazza, Nuclear properties of magnet structural materials for fusion reactors, J. Nucl. Matl. 179-181 (1991) 1123-1126.

* Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48 and Ministerio de Educación y Cultura, Spain, under Project DGCIT PB95-0230